

## 1.2 - ACTS Ka-Band Earth Stations: Technology, Performance, and Lessons Learned

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### Abstract

The Advanced Communications Technology Satellite (ACTS) Project invested heavily in prototype Ka-band satellite ground terminals to conduct an experiments program with the ACTS satellite. The ACTS experiment's program proposed to validate Ka-band satellite and ground station technology, demonstrate future telecommunication services, demonstrate commercial viability and market acceptability of these new services, evaluate system networking and processing technology, and characterize Ka-band propagation effects, including development of techniques to mitigate signal fading.

This paper will present a summary of the fixed ground terminals developed by the NASA Glenn Research Center and its industry partners, emphasizing the technology and performance of the terminals (Part I) and the lessons learned throughout their six year operation including the inclined orbit phase of operations (Full Report). An overview of the Ka-band technology and components developed for the ACTS ground stations is presented. Next, the performance of the ground station technology and its evolution during the ACTS campaign are discussed to illustrate the technical tradeoffs made during the program and highlight technical advances by industry to support the ACTS experiments program and terminal operations. Finally, lessons learned during development and operation of the user terminals are discussed for consideration of commercial adoption into future Ka-band systems.

The fixed ground stations used for experiments by government, academic, and commercial entities used reflector based offset-fed antenna systems ranging in size from 0.35m to 3.4m antenna diameter. Gateway earth stations included two systems, referred to as the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET). The NGS provides tracking, telemetry, and control (TT&C) and Time Division Multiple Access (TDMA) network control functions. The LET supports technology verification and high data rate experiments.

The ground stations successfully demonstrated many services and applications at Ka-band in three different modes of operation: circuit switched TDMA using the satellite on-board processor, satellite switched SS-TDMA applications using the on-board Microwave Switch Matrix (MSM), and conventional transponder (bent-pipe) operation. Data rates ranged from 4.8 kbps up to 622 Mbps. Experiments included: a) low rate (4.8-100's kbps) remote data acquisition and control using small earth stations, b) moderate rate (1-45 Mbps) experiments included full duplex voice and video conferencing and both full duplex and asymmetric data rate protocol and network evaluation using mid-size ground stations, and c) link characterization experiments and high data rate (155-622 Mbps) terrestrial and satellite interoperability application experiments conducted by a consortium of experimenters using the large transportable ground stations.

## Ground Stations Overview

The ground stations developed by NASA Glenn Research Center and its industry partners included five different size terminals each with unique capabilities designed to meet a set of applications for experiments and demonstration at Ka-band. The large ground station facilities of the ACTS/GRC program are the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET). The NGS serves as a) primary tracking telemetry and control (TT&C) station of ACTS, b) reference station of the Baseband Processor (BBP)/VSAT TDMA network, c) two VSAT traffic terminals, and d) backup facility to the LET for MSM experiment operations. The LET serves as a) hub for USAT star network experiments, b) High Data Rate terminal in the Gigabit Network, c) experimenter station used to conduct technology verification experiments such as wideband dispersion and antenna wetting, d) on-orbit test-bed for ACTS s/c characterization measurements including frequency response, and multi-beam antenna characterization, and e) backup facility for the TT&C function of the ACTS satellite.

The family of experimenter or transportable ground stations includes the Very Small Aperture Terminal (VSAT), the Ultra Small Aperture Terminal (USAT), and the High Data Rate (HDR) Terminal. Each terminal was originally designed to support certain applications. As advances in technology occurred over the course of the program each terminal demonstrated more advanced applications further demonstrating the capabilities of ground stations at Ka-Band. The VSAT terminal and ACTS TDMA network was initially used for 1.544 Mbps video and voice conferencing based on 64kbps channels and fade compensation algorithm evaluation. Over the course of the program the terminals were deployed for protocol networking experiments, propagation data collection & analysis, statistical availability for a TDMA network, and technology experiments to evaluate the satellite multi-beam antenna performance. The USAT ground stations were originally designed to demonstrate supervisory control and data acquisition for remote electric utility stations using kbps data rates. Advances, primarily in solid state amplifier technology, enabled the stations to demonstrate >1.544 Mbps video conferencing, highly asymmetric (1.544/45 Mbps) product and content distribution applications, and 2 Mbps full mesh TDMA/FDMA IP and ATM network experiments. The HDR station was first deployed to demonstrate interconnectivity of super computers to conduct interactive computer modeling at high data rates. Over the duration of the program the stations were re-deployed to demonstrate high rate commercial IP protocol augmentation, optimized FTP file transfer, and technology verification experiments and characterizations.

The ACTS satellite has two modes of operation; the MSM and BBP. The MSM mode of operation functions as a bent-pipe memory-less repeater with frequency translation. A microwave switch at the satellite IF frequency connects uplink antennas to appropriate downlink antennas for static point-to-point connections. The MSM may also be programmed using a repeatable uplink/downlink connection sequence for a satellite switched TDMA (SS-TDMA) network for HDR operations. The BBP provides on-board storage and routing of base-band signals for the VSAT TDMA network. Signals from each transmitting VSAT are demodulated by the BBP on-board the satellite and routed to the appropriate receiving station by illuminating the appropriate spot beam over the respective transmitting and receiving station<sup>1</sup>. The satellite burst time plan dynamically updates based on orderwire requests from stations entering the network or if existing stations change their bandwidth requirement<sup>2</sup>.

Table 1. ACTS GROUND STATION SUMMARY

NAME	MODE	ANTENNA (m)	HPA (Watt)	ERP (dBW)	GT (dB/K)	BURST RATES (Mbps)	DATA RATES (Mbps)	MODULATION
NGS	BBP	5.5	200	68/74	26.5	U/L: 27.5 or 110 D/L: 110	64 kbps to multiple T1 & T2	SMSK
VSAT	BBP	1.2	12	60/66	16	U/L: 27.5 D/L: 110	1.792 (max) at 64 kbps increments	SMSK
USAT	MSM	0.6, 1.2	.25, 1.0, 2.0	35-51	13/16	Up to 2.5 Msps	U/L: low kbps to 8 Mbps D/L: up to 45 Mbps	BPSK, QPSK, CDMA
HDR	MSM	3.4	100	76	28	Up to 696	311 or 622 Mbps	O-BPSK (OC-3) O-QPSK (OC-12)
LET	MSM	4.7	10-60	68-76	27	Up to 696	low kbps to 622 Mbps	BPSK, QPSK, SMSK

Table 1 identifies each ground station, its primary mode of operation, and typical link characteristics. The LET, HDR, and USAT terminals operate in the MSM mode and each use various modulation schemes. Because the transponders use hard-limiting amplifiers higher order modulation schemes above QPSK were not used. The NGS and VSAT operate in the BBP mode of the ACTS satellite. The modems on both the spacecraft and ground stations employ Serial Minimum Shift Keying (SMSK) modulation.

The ACTS ground station program enabled the commercial industry to make advancements in the design and performance of traveling wave tube amplifiers (TWTA's), low noise amplifiers, high rate modems, solid state power amplifiers, and high power frequency doublers. In addition, although outside the scope of this paper, the development of the on-board processing TDMA network enabled various satellite and ground station technologies not addressed here. The implementation of commercial terrestrial interfaces laid a foundation for terrestrial and satellite interoperability experiments, commercial protocol research and augmentation, and other technical advancements. The RF technologies developed for the ACTS ground terminals, with a few exceptions, were mainly extensions of technologies developed at lower frequency bands. Still, the design challenges were quite real and required significant engineering effort to overcome. The final result was high-quality ground station equipment that continued to perform well beyond the intended operational life of the system.

### Ground Stations Technologies

#### Transmitter

Development and operation of 30 GHz Ka-band traveling wave tube amplifiers (TWTA) proved challenging in the early years of ACTS. The NGS and LET were the first to procure 30 GHz TWTA's. The NGS and LET began ground station integration and testing in the late 1980's and early 1990s. The NGS purchased four 54-Watt units and later the LET purchased three 60-Watt units from the same vendor. The TWT design used in the LET was similar to those used in the NGS. The TWT's were linear beam devices with a helix type slow-wave microwave circuit.

These first TWTA's experienced several problems. The first anomaly was reported in 1992<sup>3</sup> that described a spontaneous shut down of the TWTA protection circuitry. Testing revealed random output power spikes (1-3 dB RF power fluctuations) present at certain frequencies. Naturally, the random power spikes contributed to loss of data bits and resultant increase in Bit Error Rate (BER). The effect would appear in the 10<sup>-8</sup> BER range. Strong spikes resulted in the spontaneous shut down of the TWTA. Test data and analysis provided to the vendor contributed to modifications in TWTA design to minimize the effect of the power spikes. Although TWTA's in general experience RF fluctuations, the low BER experiments conducted in the ACTS program were more susceptible to these types of component characteristics. Other problems that occurred were high helix current shut off and an inability to power a unit on. Over time the latter problem was attributed to the operational procedure of the TWTA's.

The operations procedure at the start of the program was to allow the TWTA to run without RF drive during short periods of inactivity and turn the TWTA off during longer periods of inactivity (e.g., overnight). Regularly turning the unit off and on or leaving the unit turned off for short periods of time tended to create gas in the vacuum envelope of the tube. This resulted in a high helix current causing the helix protection circuitry to power the unit off or prevent the unit from turning on. It is also believed that the operational practice led to shortened TWTA life. These practices and the technical problems mentioned resulted in regular occurrences of TWTA malfunctions and lengthy repair cycles. The TWTAs were routinely sent to the vendor to repair high voltage components or to degas the unit. Due to the sporadic shut-offs and operational difficulties, the original TWTA's were never run to end of life and were replaced by a next generation TWT from the same vendor (for LET) and new TWTAs from other vendors for both NGS and LET. The original TWTA's had 7,000-10,000 hours before removal from service.

The TWTA operations procedure for both LET and NGS was changed such that energized tubes were never permitted to idle for long periods of time, without high voltage applied. They were always operated with an applied carrier, either radiated or transmitted into a dummy load. Particular attention was also paid to maintaining proper cooling. This resulted in a very stable operating environment, significantly extending TWTA service life.

The combination of change in operational procedures and improvements made in the second-generation TWTAs used in the LET increased TWTA service life. The new TWTA (from original vendor) was removed from service with over 20K hours of operation. The helix current remained stable and only increased near end of life, as expected. The LET TWTA from the second vendor provided 100 Watts output power using a 120-Watt tube. Internal components, primarily the output isolator, account for the losses. The TWTA's also employed a helix type structure tube and power supply in a single housing. The second vendor's TWTA has been in service at LET for over 22,000 hours as of this writing.

Replacement TWTAs for both the NGS and LET were procured from new and different vendors than the original TWTAs. The NGS tubes are capable of 200-Watt output, but internal component losses and biasing result in a saturated power level of 150 Watt at the amplifier output. The slow-wave structure of the tube is a coupled cavity, i.e., the tube does not have an actual helix, but rather an inter-digital delay line that performs the same function as a helix. The circuit was developed as a better way of realizing the slow-wave structure, given the high power level and the stringent size and accuracy requirements in the mm-wave range. This design, however, is not as broadband as tubes using actual helices. The NGS TWTAs use a split mount design with separate units for the TWT and power supply.

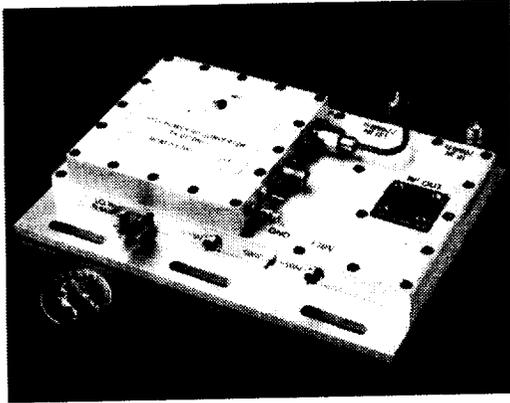
The design life of the second generation NGS TWT collector and electron gun are 20,000 to 30,000 hours. The original tubes delivered with the new TWTAs lasted 10,000 to 12,000 hours, with one premature failure at 2,700 hours. The failures occurred for various reasons, including materials used in the tube, mechanical shock, and the precision tolerances required in the tube structure at Ka-band. Another factor was the stability of the delay line inside the tube. The attenuation of each section must be stable over the operating temperature range to avoid problems with gain ripple. As experience was gained with tube operation in the NGS and with other users, the vendor examined tube failures and made improvements in the tube design and materials used. The design changes resulted in similar tube design life but achieved a much longer operating life - closer to 30,000 hours.

The VSAT transmitter used Ku band TWTs operating at 14.6 GHz combined with a High Power Frequency Doubler (HPFD). The TWT, power supply, and fault circuits were enclosed in the Intermediate Power Amplifier (IPA). The unit produced +45 dBm with a -5 dBm input signal. The IPA drives the HPFD to produce the final output frequency of 29.2 GHz at +40.5 dBm. The IPA burst with a 25 % duty cycle under normal conditions. AC power is applied to the unit at all times and monitored on an hour meter. The average life of each IPA is about 26,000 hours or three years. The IPA power supplies were typically the first to fail. Repairing the power supply units would extend the TWT life to about 30,000 hours.

With the decision to extend the ACTS program in late 1995, after the initial experiment phase (2 years), most VSAT TWT's and HPFDs were in their third year. Due to the IPAs reaching end-of-life and design issues with the HPFD, the project had to decide to stay with the IPA and HPFD design or use new 30 GHz Solid State Power Amplifiers (SSPA) capable of the required 10-12 Watt output power. The SSPA's were available from a limited supply of vendors. However, the output power specification was difficult to meet and some manufactures could not guarantee a reliable product. Because the change in technologies would incur

substantial cost and increase risk, the project stayed with the IPA/HPFD design and replaced the IPAs entirely and redesigned the HPFDs.

**Figure 1. USAT 1-WATT  
UPCONVERTER/AMPLIFIER MODULE**



the original units continued to fail. Although the new HPFD design was more reliable than the original, the units were still the source of many VSAT failures. Experience and testing with the VSAT determined that the IPA's produced voltage spikes that degraded the HPFD over time. The IPA/HPFD redesign significantly improved the system availability of the VSAT network. Although the technology used required regular terminal maintenance, the reliability data of both the IPA and HPFD enabled system engineers to plan repairs and service each station before unexpected failures occurred and reduced troubleshooting time to minimize impact to the experiments program.

The USAT transmitters employed low power solid state power amplifiers. In the early 1990s, cost and availability limited these discrete component amplifiers to .25 Watt. Combined with a single-stage upconverter from 800 MHz to 30 GHz, the resultant package was a small 5"x3"x1" upconverter/amplifier integrated near the feed of the antenna to minimize loss. As solid state technology matured a second version of the block upconverter was produced in 1997. The second generation used 1-Watt Monolithic Microwave Integrate Circuit (MMIC) amplifiers with a two-stage upconverter (70 MHz to 30 GHz), yet only a small increase in size resulted. The new units measured 5"x4"x1" as shown in Figure 1. In addition, 2-Watt units were also produced in the same size package by combining two 1-Watt MMIC chips. The challenge of these higher power units was achieving good component yield and hand selecting the highest power chips for integration. This resulted in good overall performance and stable operation over temperature with losses of only 1-1.5 dB at 80°C. Solid state amplifiers in the 4-10 Watt range were also available in the late 1990's but cost and integration prohibited their use. The goal of the USAT was modest data rate (>1.544 Mbps) with small packaging, which was achieved with the one and two watt units. As successful as these units were in size, operation, and performance, advances are still needed in device yield and unit production and integration to make these products affordable for the mass market.

The HDR station also employed 30 GHz high power TWTAs. The units were a split-mount design with a 12m umbilical cord to remotely control and supply power to the TWT. The TWT was mounted on the boom of the antenna near the feed with the power supply and pre-amp rack mounted inside the HDR equipment trailer. Like the LET the TWT was designed around a helix type slow-wave microwave circuit with an output of 100-120 Watts with > 1 GHz bandwidth. Unlike other terminals, HDR TWTAs remained powered down for the majority of the time, per recommendation of the TWT vendor (different from NGS & LET), despite the experience gained in the NGS and LET operations. TWT operations without high voltage applied were limited to only a few minutes.

The TWT used in the beginning of the project had an extremely high failure rate. The high failure rate was contributed to the following: (a) water penetrating the outdoor high-voltage connectors shorting out the power supply; (b) high-voltage shorting out to chassis due to faulty potting process; and (c) temperature fluctuations causing the TWT to defocus. In addition to the high failure rates, turn-around time on defective units was excessive. In mid-1997 a different vendor was selected to provide TWTAs for the HDR project. TWT performance and reliability improved.

The first HPFDs used in operation were not designed to operate with a continuous wave (CW) signal applied. Prior to launch, the project identified the need to characterize and test the HPFD with a CW signal during operations. A second problem with the original HPFD was they operated at high temperatures and several units failed after only a few months due to diode failures. Each HPFD had four diodes that produced the output power and frequency doubling. The new units produced were designed for CW, operated at lower temperature and used a different diode biasing design. Other design changes included a new balanced diode assembly and additional heat sinks applied to each individual diode. Reduced VSWR made the diode less susceptible to standing waves and voltage spikes. The entire fleet of VSAT's (19) was upgraded with a new HPFD as

**Table 2. TRANSMITTER TECHNOLOGY SUMMARY**

Station	Technology	Initial Issues	Advancements / Lessons Learned
NGS	54 Watt Single Chassis	<ul style="list-style-type: none"> <li>- Sporadic shutdowns</li> <li>- RF power transients</li> <li>- Low reliability</li> </ul>	<ul style="list-style-type: none"> <li>- Improved gun insulation and insulation application procedure.</li> </ul>
	150 Watt TWTA-split mount	<ul style="list-style-type: none"> <li>- TWT failure at 10000-12000 hours</li> <li>- Cooling fans</li> </ul>	<ul style="list-style-type: none"> <li>- Modified tube design and operational changes led to &gt;30000-hour tube life with minimal service.</li> </ul>
VSAT	12 Watt Ku-Band TWT, HPFD	<ul style="list-style-type: none"> <li>- HPFD reliability</li> </ul>	<ul style="list-style-type: none"> <li>- New HPFD diode and heat sink design</li> <li>- Technology gaps remain for affordable Ka-band 10-12 Watt SSPA.</li> </ul>
USAT	.25-2 Watt Solid State/MMIC	<ul style="list-style-type: none"> <li>- Solid state and MMIC cost and availability</li> </ul>	<ul style="list-style-type: none"> <li>- Single integrated block upconverter/amplifier</li> <li>- Advancements in MMIC made devices more available.</li> <li>- Reduction in cost &amp; integration required enabling consumer terminals.</li> </ul>
HDR	120 Watt TWTA-split mount	<ul style="list-style-type: none"> <li>- Low reliability</li> <li>- Environmental effects</li> </ul>	<ul style="list-style-type: none"> <li>- Identified potential high voltage interface issues of outdoor installed split mount TWTA's</li> <li>- Environmental concerns remain for precision tolerances required for Ka-band TWTA operation.</li> </ul>
LET	60 Watt TWTA Single Chassis	<ul style="list-style-type: none"> <li>- Sporadic shutdowns</li> <li>- RF power transients</li> <li>- Low reliability</li> </ul>	<ul style="list-style-type: none"> <li>- Improved gun insulation and insulation application procedure.</li> </ul>
	100 Watt TWTA Single Chassis	<ul style="list-style-type: none"> <li>- None</li> </ul>	<ul style="list-style-type: none"> <li>- Operational changes led to &gt;22000-hour tube life with minimal service.</li> </ul>

Table 2 summarizes the transmitter technology used in each ground station. A number of different approaches were taken with each station because of its experiment and application requirements. Design changes in TWTA material and integration, changes to TWTA operation procedures, and advancements by industry in solid state and MMIC amplifiers were highlights of this technology area.

### Receiver

Receiver technology experienced modest advancements during the ACTS program. The majority of the low noise amplifiers and low noise converters (LNA/LNC) were built to specification often at or slightly advance of state of art at the time. Most of the devices used, with the exception of the VSAT LNC, were technically good devices lasting many years of service.

The NGS LNAs employed quarter-micron HEMT FETs, which were the state of the art in the late 1980s when the station was built. Two sets of LNAs are used, one at 20 GHz for the TDMA downlink and telemetry beacons, and one at 27.5 GHz, for the transmit band propagation beacon.

The 20 GHz LNA subassemblies are implemented in a cascade of two stages, each with a gain of 30 dB and a noise figure of 3.0 dB. The station employs three such LNA subassemblies, in a 3-for-2-redundancy configuration. The total system noise temperature, referenced to the antenna output, is 570K. This value includes an antenna temperature of 123K and an effective system electronics temperature, including waveguide loss, of 447K.

The 27.5 GHz LNAs also employ two stages, each with a gain of 20 dB and a noise figure of 4.5 dB. The total system noise temperature, referenced to the antenna output, is 1687K. This value includes an antenna temperature of 121K and an effective system electronics temperature, including waveguide loss, of 1566 K.

The NGS LNAs have been in nearly continuous operation, either in test facilities or on the air, since 1991. They have proven to be a robust technology. Few failures occurred over their 9 years of operation, most explained by environmental incidents, i.e., periods of high ambient temperature due to facility HVAC failures or inadvertent signal overload, rather than device failure. Periodic maintenance checks indicated little or no degradation in device performance over the period of service.

The original LET 20 GHz receiver/downconverter used a four-stage HEMT LNA followed by an MMIC mixer and amplifier stages to downconvert the signal to the Intermediate Frequency (IF) frequency of 3-4 GHz. There were three such units produced under a proof-of-concept (POC) development effort. The LNA and downconverter had a combined noise figure of approximately 4 -5.5 dB, with a nominal gain of 25 dB. While the POC units exhibited excessive gain slope across the full 1 GHz downlink band, they exhibited only modest gain slope across their operational band (300 MHz) and were quite usable for applications within that bandwidth. Consequently, they were incorporated into the initial station build-up and used for relatively narrow band signal applications, as an efficient use of existing hardware and a cost saving measure early in the program. However, because of their gain slope across the full band, the POC units proved unusable for wideband applications, such as on-orbit link and spacecraft characterization experiments of the entire transponder bandwidth, and emerging high data rate modem technology requiring larger bandwidths with minimum gain slope. To accommodate these wider bandwidth applications, it was eventually necessary to replace the POC units with receivers tailored for that purpose.

The LET receivers were replaced with commercially available low noise amplifiers and an in-house designed downconverter. The LNA selected was identical to that used in the HDR stations. The LNA's exhibited 50 dB of gain with noise figure of 3.5 dB with minimal slope across the GHz band. The LNA's used in HDR and LET proved reliable over the project. Many have been in service since 1995 with little or no performance degradation. The few failures that did occur were mainly the result of physical damage to the amplifier.

The VSAT stations encountered significant challenges in the receiver design. The VSAT LNC is a 3-stage HEMT low noise amplifier, RF bandpass filter, mixer, silicon MMIC IF amplifier, voltage regulator and fault circuit. Developed in the early 1990's, the receivers exhibited a wide range in performance. The receiver gain was specified at 45 dB and the noise figure was specified at 5 dB. The performance from unit to unit differed significantly. Each unit was hand tuned at the factory as a result of the design and performance. The total receiver gain (multiple stages) ranged from 40 to 52 dB and the noise figure varied from 3 to 9 dB. These variances required that the downlink of each station be adjusted to ensure like performance and operation compared to other VSATs. Because the receiver performance varied so much between units, the entire receiver characteristics drastically changed when different receivers were installed due to failure or service. This lengthened the service time at a particular station to allow time to make necessary adjustments to account for differences in the receivers.

The first generation USAT ground stations used combined LNA and single stage block downconverters from 29 GHz to 70 MHz. Performance, small size, and low cost were the primary goals of the USAT low noise downconverters (LND's). The original LND's exhibited 25 to 28 dB gain with a 4-4.5 dB noise figure over 40 MHz bandwidth<sup>4</sup>. The units measured 4.25x2.25x.4 in. The LND could operate with 40 MHz bandwidth increments from 19.7-20.4 GHz by varying the downlink oscillator. The first generation LND's failed after three years of operation. Coincidentally, four of five units failed within the same month after varying scenarios of operation. The fifth unit failed a short time later. Each LND had a similar amount of operation time but was often located in different geographical and temperature locations. No particular operational parameter was identified as the cause of the failure.

Improvements made by industry during the 1990's resulted in improved performance for the second generation LNDs. With a similar size package, the new LND's had 32 dB gain with a 2-2.5 dB noise figure over 50 MHz bandwidth. A total of 15 units were purchased in 1997 with all units exhibiting similar gain and noise figure performance. These units also covered the 19.7-20.04 GHz spectrum but had larger receive bandwidths of 50 MHz (compared to 40 MHz). With the improved noise figure, these units raised the available data rate between small ground stations making them more adaptable to a variety of applications<sup>5</sup>.

### **Antenna**

All the antennas used with the transportable experimenter ground stations were offset fed parabolic reflectors. The USAT and VSAT reflectors were actually Ku-band reflectors, which proved adequate for operation at Ka-band. However, propagation experiments conducted on the antennas revealed that wet antenna effects of Ku-Band antennas operating at Ka-Band resulted in greater loss due to the rainwater and the thickness of the Ku-band dielectric. Minimizing the dielectric thickness at Ka-Band is needed to reduce loss in the presence of water on the reflector<sup>6</sup>. As much as 2-5dB is lost due to wet antenna and feed radome effects.

The HDR station was the only experimenter station antenna in the ACTS program made up of individual panels. The USAT and VSAT reflectors (.6m, 1.2m, and 2.4m) were all one-piece structures. The 3.4m HDR antenna was made up of four individual panels. Station performance validated that using this type of sectioned reflector is a viable alternative for Ka-band operation compared to a single piece reflector. Surface tolerance and feed alignment were adequate for operation.

Both the NGS and LET antennas employ cassegrain-type feed systems. The LET antenna uses the more conventional configuration, in which the feed horn extends from the apex of a 4.7m dish and couples the reflector optics to transmit and receive equipment located in a hub assembly immediately behind the reflector. The NGS employs a beam waveguide system, which couples an aperture at the apex of a 5.5m dish to a feed horn located at the base of the antenna. The feed horn then connects to transmit and receive equipment located indoors in a room directly beneath the antenna.

The NGS feed network follows the feedhorn and consists of a half-wave polarizer and orthogonal mode transducer (OMT) connected by rotary joints. This network allows the antenna to receive and transmit in dual orthogonal linear polarizations, with two 20 GHz receive ports and two 30 GHz transmit ports. The 27.505 GHz transmit band satellite beacon is also received at one transmit port and is separated from the transmit signal at that port by a multiplexer and filter assembly. The antenna polarization angle is adjustable through 360 degrees by rotating the polarizer, to match the antenna polarization to that of the satellite signals.

The LET antenna feed network is a combined corrugated horn and OMT assembly. Waveguide for both transmit and receive extend past the polarizer and into the antenna hub. The polarizer has 4 slots along its radius corresponding to bolts on the antenna structure to allow polarization adjustments upon installation. Polarization is adjusted by physically rotating the combined polarizer/feed assembly until peak signal is reached. Polarization of LET was an iterative process because of the rigid waveguide connections inside the hub. Flexible and rotary joint waveguide would ease the procedure, but it remains a physically challenging task.

Early in system operations a correlation was noted between a decrease in signal level and operation of the NGS antenna deicing system<sup>7</sup>. At the time it was thought that the observed effect could be a combination of antenna wetness from melting snow and thermal distortion of the antenna reflector. Further investigation confirmed both theories. Antenna wetting effects at Ka-band have been investigated by several people and have been quantified as an additional source of link degradation<sup>8</sup>. Also, subsequent maintenance of the NGS antenna revealed that the deicer heating system did cause thermal distortion of the antenna structure, which reduced antenna gain. Modification of the heating system reduced the effect, although it is still observable, particularly at high heat settings.

These heating effects will vary with antenna design, but the experiences gained point out the need for careful attention during the design process to all potential sources of mechanical deformation to maintain the close surface tolerances required of Ka-band antenna reflectors. The potential usefulness of specific design features to mitigate water and icing effects on the antenna structure should be noted, e.g., through the use of shields or other devices to reduce water accumulation on particularly sensitive areas of the antenna.

### **Modems**

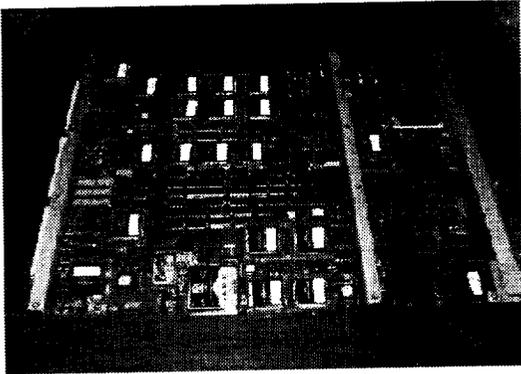
The combination of the ACTS satellite and the extensive ground station program enabled a number of advances in modem technology and the demonstration of various modem implementations. From custom ground and on-board processing TDMA network medium rate burst modem to satellite switched TDMA high rate burst modems to the use of commercial off-the-shelf low rate continuous wave modems and ground-based TDMA/FDMA network low rate modems, the ACTS program enabled flexible network architectures and system configurations.

The VSAT and NGS modems supported TDMA/FDMA operation of the spacecraft onboard processor and the associated TDMA network. The spacecraft and ground station modems were the same design and operated in burst mode at 110 or 27.5 Mbps using SMSK modulation. The VSAT modems were limited to 27.5 Mbps on the uplink. As part of the network fade mitigation design, the modems could also be operated at one half their normal burst rates, 55 or 13.75 Mbps, with rate ½ Forward Error Coding (FEC) coding, to achieve a 10 dB increase in system up-link and down-link margins.

The NGS and VSAT modem design proved to be stable and well executed, and modem performance was generally excellent over the course of the program. Maintenance problems were infrequent and involved power

supplies, oscillators or cooling fans, which are normal failures associated with age and facility environmental upsets. Only one design idiosyncrasy was noted - Sensitivity to certain data patterns, e.g., long strings of 1's or 0's. This was present in both the spacecraft and ground modems, and was obviated by locking out certain data combinations.

**Figure 2. DT NETWORK PROCESSOR BOARD**



Because of the burst mode operation and the data rates involved, fault diagnosis was more challenging, particularly in the case of intermittent failures. However, the modems were delivered with special test equipment designed to exercise the 3 different modem pairs (110 Mbps uplink, 27.5 Mbps uplink, and 110 Mbps downlink). The modem special test equipment proved to be a valuable tool in stand-alone modem fault diagnosis. However, it was also incorporated into the station test equipment suite so that the modems could be exercised over the station transmit and receive chains, to verify overall station performance. Regular BER measurements were performed as part of station periodic maintenance as a check on both the modems and the amplitude and group delay characteristics of the station transmit and receive equipment.

The HDR burst modem is a dual-mode device capable of operating in offset binary phase-shift keying (OBPSK) or offset quadrature phase-shift keying (OQPSK) modulation. The symbol rate of the burst modem is 348 MS/s, providing data-rates of 311 Mb/s in OBPSK or 622 Mb/s in OQPSK. Of the six modems designed and built for the HDR program three remained in service and fully functional to the end of the inclined orbit program, operating for over two years without repair. Although the modems performed soundly, it is believed the addition of adaptive equalizers to the demodulator front-end to compensate for the satellite non-linear transponder and changes in the system due to aging would have enhanced performance.

The companion to the high data rate burst modem was the Digital Terminal (DT). The DT interfaced the high rate terrestrial SONET interface to the burst modem. The DT also managed/controlled the TDMA network scheduling, the Reed-Solomon FEC encoding/decoding, bit scrambling, and the operator interface. The network processor board of the digital terminal depicted in Figure 2 is one of six boards that make up the digital terminal. The DT and high data rate burst modems were custom-made equipment and the DT is arguably the most sophisticated component of the HDR station. Due to the complexity of the equipment, its interfaces, and operational issues, a large portion of the problems associated with the HDR stations were attributed to the DT.

The USAT ground stations were designed to support a wide variety of applications. Designed with a 70 MHz IF interface the station could be used with a variety of commercial modems employing standard 70 MHz interfaces. Configured with a 1Watt transmitter and .6m antenna the USAT could support 2-4 Mbps between stations with adequate margin. Configured with a 1.2m reflector, experiments were conducted using 6-8 Mbps. Higher data rates could be achieved by employing Reed Solomon coding or reducing the available link margin on clear days. The modems allowed the stations to offer a variety of serial and data interfaces such as RS-232, RS-449, DS-1/E1, IP, ATM, Frame Relay, ISDN, DS3, and HiSSi, (high-speed serial interface). All the interfaces mentioned were used with the USAT ground stations for testing or experiment applications during the program.

Because the stations were not dependent nor required a specific modulation, various modulation schemes were used. Most experiments used either QPSK or BPSK, however CDMA was also used on one occasion. Although the USAT station did not prohibit higher order modulation schemes, the hard limiting amplifiers on-board the ACTS satellite degraded the performance of these schemes and they were therefore not used<sup>9</sup>. The USATs also demonstrated a ground based TDMA/FDMA mesh network using commercial products. A four node full-mesh USAT network was configured and demonstrated. Burst rates of 5 Mbps using QPSK modulation yielded nearly 2 Mbps per node with rate 1/2 Viterbi and Reed Solomon coding. ATM, IP, and Frame Relay networks operated simultaneously between stations.

The LET also provided modem flexibility. A set of variable rate burst modems from 1 to 220 Mbps operating at 3 GHz IF were built into the station. The modems were part of a proof of concept program in the late 1980's.

The modems were similar to the VSAT and NGS modems employing SMSK modulation. A custom digital interface was developed in-house to handle satellite tracking and timing and included a custom bit error rate test capability. The modems were used to test and characterize the station prior to satellite launch. Shortly after launch a 70 MHz interface was designed for the LET allowing commercial modems used by the USAT stations to operate with LET. The commercial modems handled all satellite tracking functions and standard bit error rate test sets were used. The proof-of-concept SMSK modems were considered the high data rate capability prior to HDR concept in early 1990's. The drawback of the custom capability was the lack of user interfaces to conduct applications or experiments using the modems. Although the use of the modems was limited to system characterization BER measurements, they still provided valuable data on the performance of the ground station and subsystems and were used to conduct high rate interference experiments with a companion ground station at GRC with identical modems<sup>10</sup>.

## Conclusion

The ACTS program developed, demonstrated, and characterized Ka-Band technology and provided lessons learned for consideration to future commercial Ka-Band systems. Advancements in traveling wave tube amplifiers low noise receivers, antennas, modems, solid state power amplifiers, and other high frequency devices, were made by the communications industry to support the ACTS ground stations.

The ACTS project had two types of ground stations; transportable field earth stations and gateway earth stations. Field stations ranged in size from 0.35m to 3.4m and conducted experiments using data rates from 4.8 Kbps to 622 Mbps. The gateway earth stations provided a) telemetry, tracking, and control of the satellite, b) the reference station of the BBP TDMA network and MSM SS-TDMA network, and c) conducted high data rate interoperability experiments and link characterization experiments. The Ka-Band technologies described in this report were applied in various ways among the field and gateway earth stations.

This report summarizes the Ka-Band technologies used in each earth station during the program. Highlights of TWTA development, LNA performance, SSPA advancements, and modem performance were described. The reader is referred to the full report describing the integration and operations of the ACTS Ka-Band ground station technologies. The full report summarizes the ACTS inclined orbit operations and modifications of the ground stations to provide tracking capability.

## Acknowledgement

The authors wish to thank the many people and organizations who have contributed to the work described herein. Throughout the ground station development and operations, many technical and non-technical contributions were made. We would like to acknowledge the feedback from the experimenter community to improve station operations, the industry partners who advanced Ka-band technologies and the earth station teams and all support personnel that implemented the experiments program.

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- <sup>2</sup> *Design and Development of a Base-band Processor for the Advanced Communications Technology Satellite*, Kerry D. Lee, Motorola Government and Space Technology Group, Scottsdale, Arizona.
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- <sup>4</sup> *Test Results of a 20 GHz, Low Noise Downconverter for USAT Applications*, Gene Fijikawa, NASA Lewis Research Center and James S. Svoboda NYMA Incorporated, 1995.
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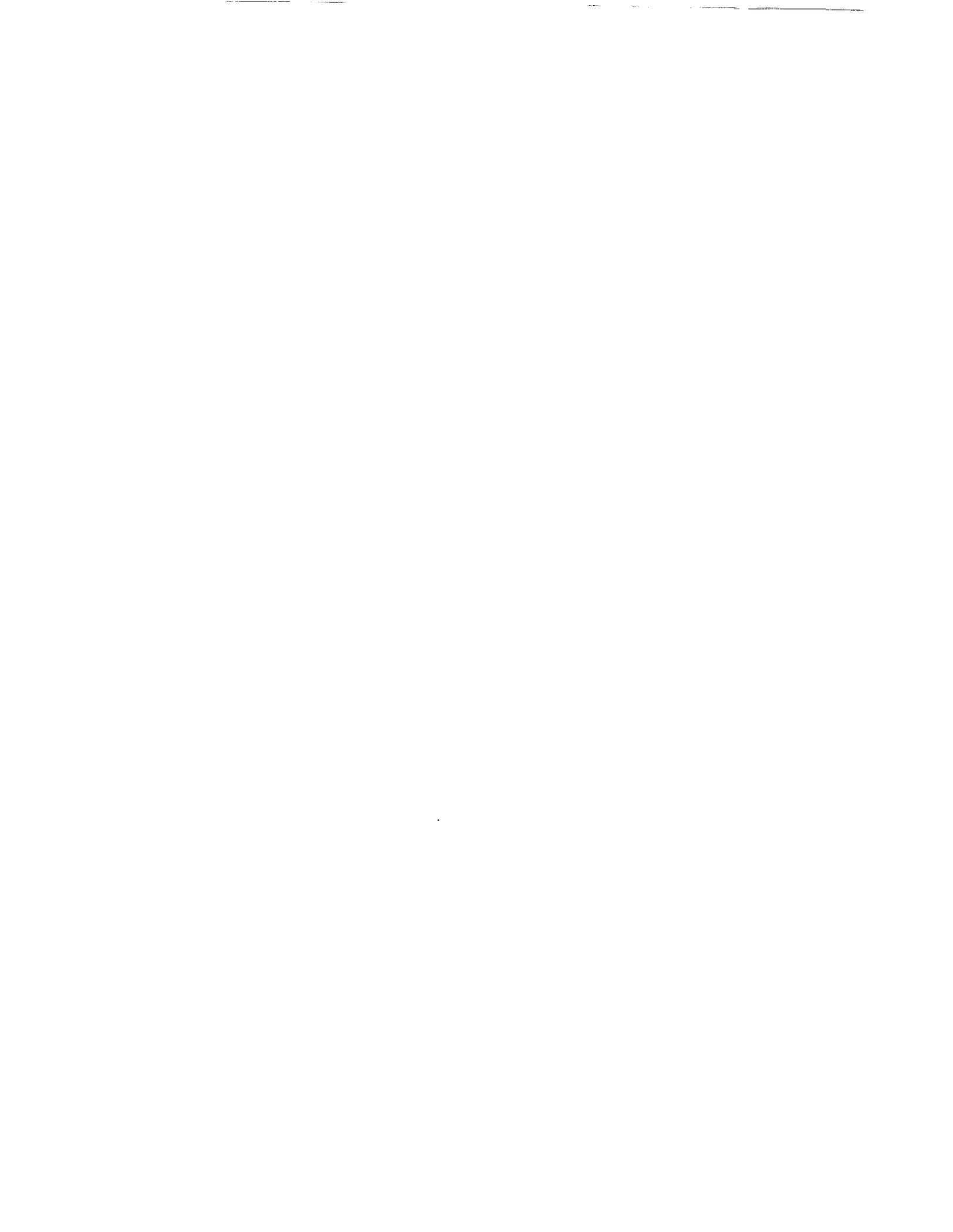
<sup>6</sup> *Special Effects: Antenna Wetting, Short Distance Diversity, and Depolarization*, Roberto J. Acosta, NASA Glenn Research Center, Sixth Ka-Band Utilization Conference, Cleveland, Ohio, June, 2000.

<sup>7</sup> *The ACTS Master Ground Station Design and Performance*, S. J. Struharik and D. N. Meadows, ACTS Results Conference, Cleveland, Ohio, September 1995.

<sup>8</sup> *Six Years of ACTS Technology Verification Experiment Program Results*, Roberto J. Acosta and Sandra Johnson, NASA Glenn Research Center, Fifth Ka-Band Utilization Conference, October 1999.

<sup>9</sup> *Modem Characterization through a Wide-Band Hard-Limiting Ka-Band Satellite Channel*, Richard C. Reinhart, Fifth Ka-Band Utilization Conference, Sicily, Italy, October 1999.

<sup>10</sup> *CW Interference effects on High Data rate Transmission Through the ACTS Wideband Channel*, Robert K. Kerczewski, NASA Lewis Research Center, Brian Kachmar, ANALEX Corporation, James S. Svoboda, NYMA Technology, Technical Paper, 1995.



# 1.2 - ACTS Ka-Band Earth Stations: Technology, Performance, and Lessons Learned

Richard C. Reinhart  
NASA Glenn Research Center  
Cleveland, Ohio

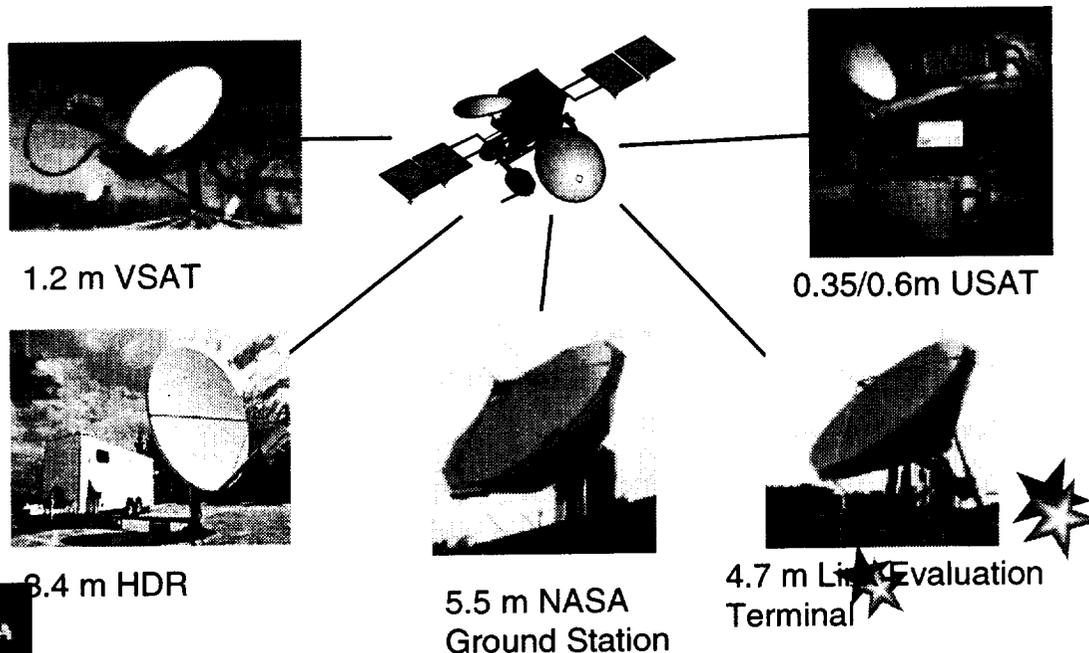
John. J. Diamond  
Analex Corporation  
Brookpark, Ohio

Steven J. Struharik  
COMSAT Laboratories  
Clarksburg, Maryland

David Stewart  
GTE  
Cleveland, Ohio

Sixth Ka-Band Utilization Conference/ACTS Conference 2000, May 31 - June 2, 2000, Cleveland, Ohio

## ACTS Ground Stations



# Transmit - 1st Generation TWTA

- **Design & Performance (NGS & LET)**
  - 60 Watt helix type TWT's
  - RF power fluctuations degraded link
  - Low reliability/spontaneous shut down/high helix current
    - Removed from service after 7,000-10,000 hours
- **Lessons Learned**
  - Tube redesign minimized RF "ticks"
    - Insulation, material, and wire changes
  - Operation procedure changed
    - Limited standby operation
    - RF drive always applied
    - Extended 2nd Generation TWT life to > 20,000 hrs



3

# Transmit - 2nd Generation TWTA

- **Design & Performance**
  - 100-200 Watt coupled cavity and helix TWT's
    - Overall performance good
  - High failure rate of outdoor installed TWT (HDR)
    - Water penetrating connectors
    - High voltage shorts
    - TWT defocus due to temperature
- **Lessons Learned**
  - Commercial design improvements continued
    - Material change, precision tolerances, delay line stability
    - Increased TWT lifetime to 20,000-30,000 hours
  - Operational procedure different for HDR TWTA's
    - Low duty cycle



4

# Transmit - VSAT

- **Design & Performance**

- Combined 40W Ku-Band TWT and frequency doubler
- HPFD located near feed in separate housing from TWT
- Ku-Band TWT achieved ~ 30,000 hours
- Low high power frequency doubler reliability
  - RF fluctuations from TWT damage diodes over time

- **Lessons Learned**

- Issues with high power frequency doubler configuration
  - Difficult to maintain stable external dc voltage bias
  - Redesigned for self biasing diodes and CW operation
- Operations data enabled personal to improve station availability

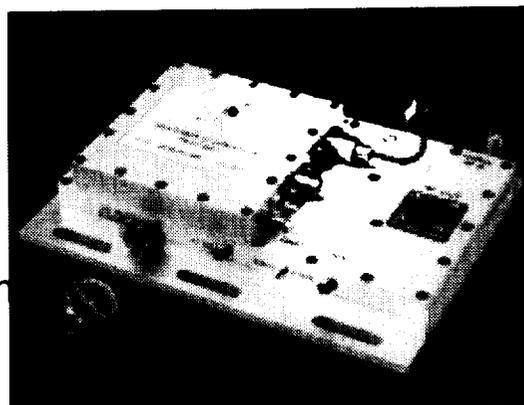


5

# Transmit - USAT/SSPA

- **Design & Performance**

- Small integrated block upconverter & SSPA
- Advancements from 0.25W to 2W MMIC amplifiers
- Good performance
- Commercial advancements in integration



- **Lessons Learned**

- Low and medium power SSPA's available but.....cost, size, efficiency, & lead time



6

# Receiver/LNA

Station	Gain (dB)	NF (dB)	Lessons Learned
NGS (20 GHz) (27 GHz)	30 20	3 4.5	HEMT LNA – Good performance, long life
LET (LNB) (LNA only)	25 50	4-5.5 3.5	Prototype/POC High gain, wider BW, good performance
HDR	50	3.5	High gain, wide BW, good performance
VSAT (LNB)	45 ± 5	5 ± 2	Wide range of performance
USAT (1 <sup>st</sup> Gen) LNB (2 <sup>nd</sup> Gen)	26 32	4.5-5 2-2.5	Advancements in NF enabled higher rate links

NASA

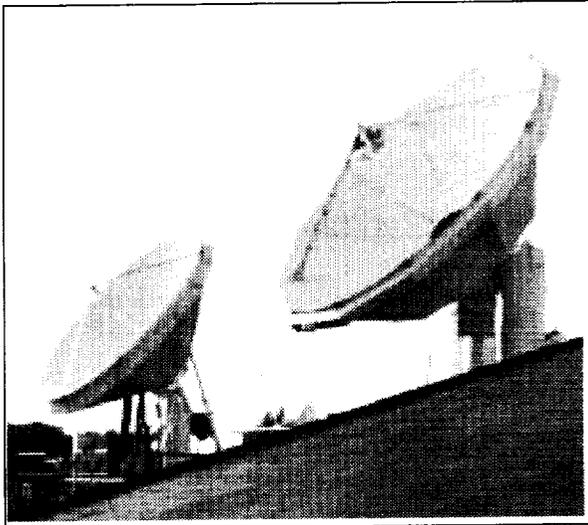
7

# Antenna - Field Stations

- **Design & Performance**
  - Parabolic offset-fed reflectors
  - Ku-Band commercial reflectors proved adequate for Ka-Band operation
- **Lessons Learned**
  - Recommend design changes to reduce wet antenna effects
    - Losses due to water coverage and dielectric thickness
  - Panel design for 3.4m antenna. Surface tolerance and alignment sufficient at Ka-Band.

NASA

# Antenna - Gateway Stations



LET

NGS

NASA

- Cassegrain
- LET - Center feed/hub mounted electronics
- NGS - Beam waveguide/ indoor electronics
- Cost/benefit analysis
- Thermal distortions caused by deicer heaters



9

# VSAT/NGS Modem/Network

- Design (SMSK)
  - Custom TDMA 27.5/110 Mbps burst modem
  - Automatic rain fade mitigation (network)
    - half-rate burst rate reduction with FEC
    - no impact or data rate reduction to user (T1)
- Lessons Learned
  - Most problems were low-tech: ps & fans
    - Only anomaly - sensitive to long strings of 1's or 0's. Corrected with S/W mod
    - Burst modems difficult to troubleshoot



NASA

10

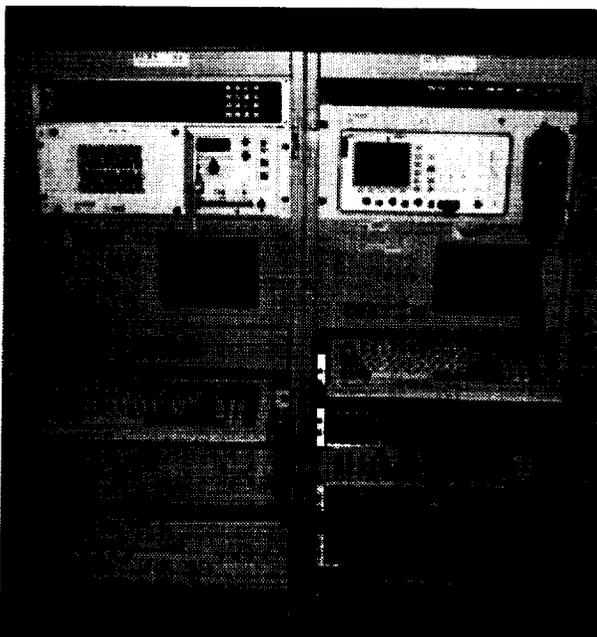
# Modems (cont)

- **HDR (O-BPSK, O-QPSK)**
  - Custom made SS-TDMA 384/696 Mbps burst modem with SONET interface
  - Four channels of OC-3 or single OC-12 throughput
  - Key technologies: fast acquisition circuitry & carrier & clock recovery functions
  - Simplify modem and digital electronics interface
- **USAT (BPSK, QPSK)**
  - Commercial variable rate (kbps to 45 Mbps) modems
  - Various serial & network interfaces
  - Diagnostics built-in, Good reliability



11

# VSAT Design



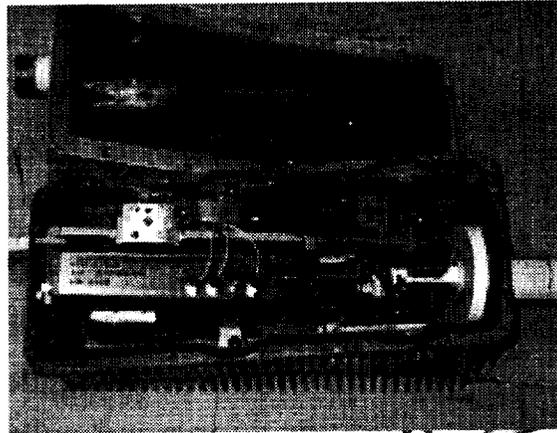
- **Extensive remote capability to monitor station (Eb/No, U/L BER, D/L BER, call parameters)**
- **Load and configure station by dial-up access or by satellite link**
- **VSAT RF enclosure**
  - Heat from HPFD effected surrounding electronics
  - Moisture damage to LNC
- **RF enclosure weather proofing**
  - Replace desiccant packs
  - Feed horn maintenance
  - Gaskets & seals



12

# VSAT Recommended Modifications

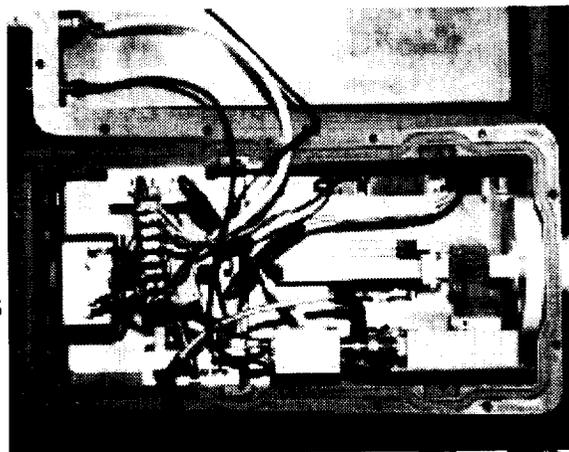
- Add RF test points and IF or RF loopback capability (relied upon TDMA network for troubleshooting)
- Move HPFD to TWT enclosure
  - Protection circuitry for RF fluctuations
  - Eliminate heat issues within enclosure
  - Adds additional WG losses
- Use Ka-TWTA or SSPA transmit @ 12-14 Watt



13

# USAT Design

- Single electronics package
- Indoor equipment - COTS modem and antenna controller provided status & control & IF loopback capability
- Limited station diagnostics by design to reduce cost and size
- 70 MHz interface



14

# USAT Recommended Modifications

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- **Reduce part count through RF design**
  - Common oscillator frequency
  - Single stage u/c
- **Reduce terminal size**
  - Integrated power supply (from indoor equipment)
  - Continued technical advancements
- **Add monitor/test points for field service**
  - oscillator lock indicator
  - output power detector
  - power supply indicator
  - RF test ports



15

# HDR Design

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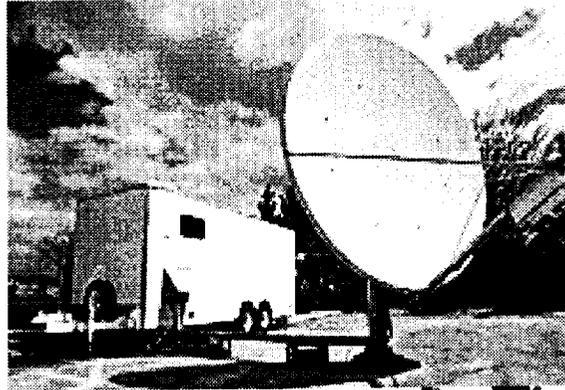
- **Used waveguide equalizers to compensate for long waveguide runs**
  - TWT mounted at antenna feed
- **High rate QPSK performance degraded by hard limiting channel & spectral re-growth**
  - Modems modified for O-QPSK, O-BPSK
- **Any station could serve as reference terminal**
- **Only station to use Internet for routine remote control & status**
  - Used dial-up and satellite link control as backup
  - Security/availability



16

# HDR Recommended Modifications

- Reduce waveguide runs to reduce group delay effects
- Strengthen antenna mount/platform or add tracking
  - Fixed mount required periodic re-pointing
- Add RF loopback to characterize station performance



17

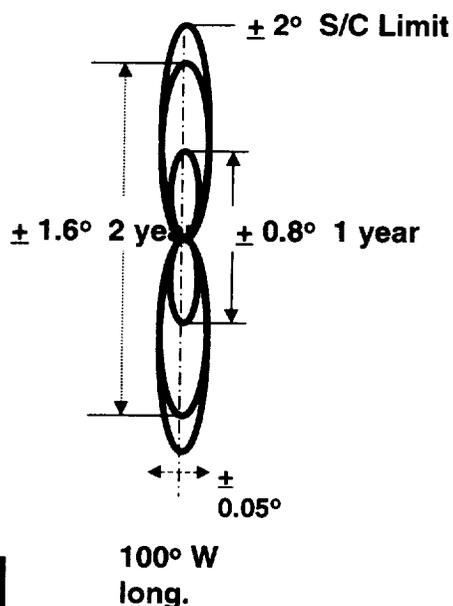
## Gateway Station Design

- Extensive diagnostic capability proved invaluable
  - IF & RF station loopback
  - Built-in test equipment
    - satellite simulator
    - modem STE
  - Pre-launch testing and check-out
  - On-orbit troubleshooting & characterization
- Validated need for stable environment and electrical power



18

# Inclined Orbit



- Satellite drift in N/S direction increasing by  $\sim 0.8^\circ$  per year
- Maintain East/West station keeping at  $+ 0.05^\circ$
- Impacts antenna tracking & TDMA acquisition & timing



19

## Inclined Orbit - Ground Station Modifications

- All stations used combination of closed loop tracking and memory track
- Antenna step tracking added to all field stations
  - Commercial controller
  - I/O mounts designed & fabricated in-house
- Modifications made to VSAT & HDR TDMA acquisition & timing s/w



20

# Inclined Orbit - Lessons Learned

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- **Step/incremental actuators proved adequate for field station antennas < 3.4m**
- **2-axis mount and closed-loop tracking with memory track proved successful**
- **Open-loop tracking evaluated/rejected**
  - periodic updates to controller
  - earth station position accuracy/stability
- **Single axis tracking evaluated/rejected**
  - installation & accuracy concerns



21

# Inclined Orbit - Lessons Learned

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- **Step track proved sufficient for Ka-Band operation.**
  - Both field and gateway earth stations
  - Fade variations affect tracking
    - Compensate with fade thresholds, fade rates, memory track
- **HDR/VSAT experienced acquisition problems late in program as expected**
  - Affected by range rate



22

# Summary

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- **Technology/Performance**
  - Highlight Ka-Band technology enabled by ACTS
  - Highlight commercial advancements of SOA
  - TWTA, HPFD/Receiver/Modems/Antenna
- **Full report in NASA publication:**
  - Station integration/operations & lessons learned
  - Inclined Orbit Operations
  - Available at Ka-Band Conference



23

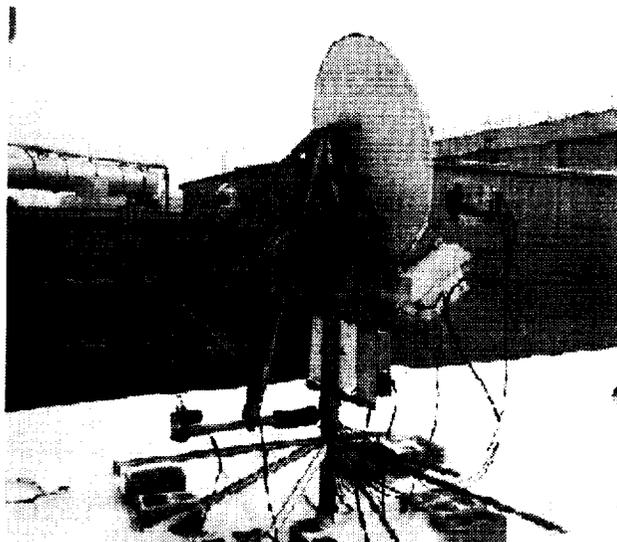
## Inclined Orbit - VSAT Mount Modifications

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**Fixed Mount**

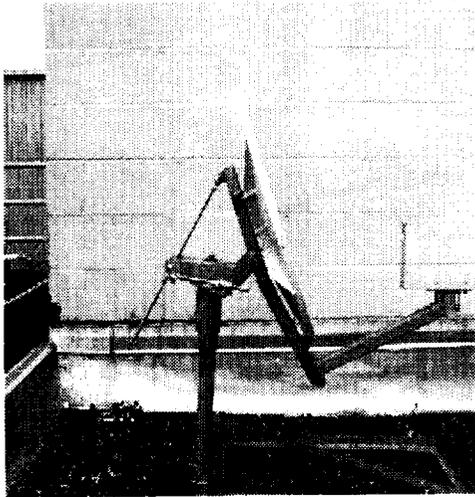


**IO Mount**

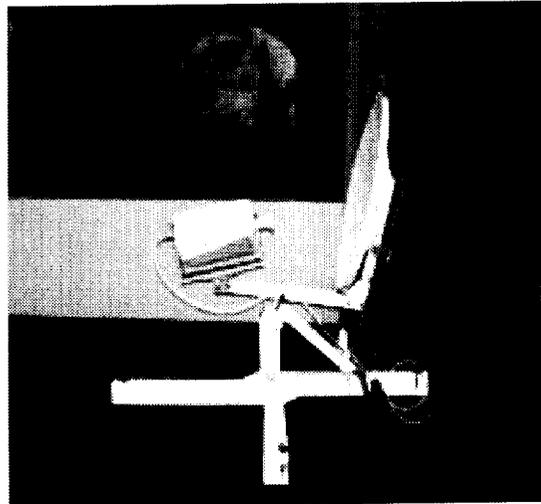


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# Inclined Orbit - USAT Mount Modifications



Fixed Mount

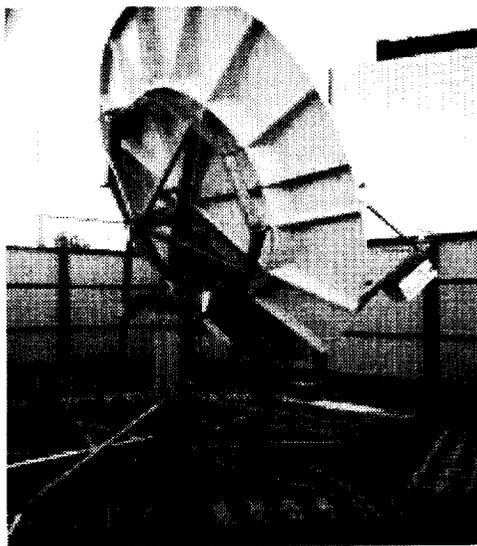


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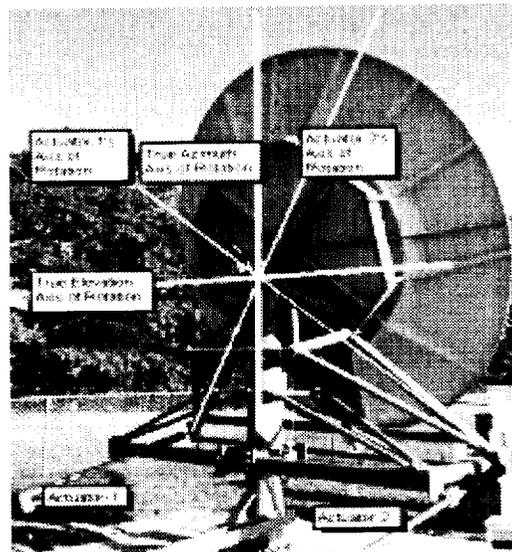


25

# Inclined Orbit - HDR Mount Modifications



Fixed Mount



IO Mount



26

# ACTS Ground Stations

NAME	MODE	ANTENNA (m)	HPA (Watt)	EIRP (dBW)	G/T (dB/K)	BURST RATES (Mbps)	DATA RATES (Mbps)	MODULATION
NGS	BBP	5.5	200	78	30	U/L: 27.5 or 110 D/L: 110	64 kbps to multiple T1 & T2	SMSK
VSAT	BBP	1.2, 2.4	12	60, 66	16-18	U/L: 27.5 D/L: 110	1.792 (max) at 64 kbps increments	SMSK
USAT	MSM	0.6, 1.2	.25, 1.0, 2.0	35-51	15, 21	Up to 2.5 MSPS	U/L: low kbps to 8 Mbps D/L: up to 45 Mbps	BPSK, QPSK, CDMA
HDR	MSM	3.4	120	76	28	Up to 696	311 or 622 Mbps	O-BPSK (OC-3) O-QPSK(OC-12)
LET	MSM	4.7	100	78	27	Up to 696	low kbps to 622 Mbps	BPSK, QPSK, SMSK

